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Sizing stand-alone photovoltaic–wind hybrid system: Techno-economic analysis and optimization

Hocine Belmili [a,*], Mourad Haddadi [b], Seddik Bacha [c], Mohamed Fayçal Almi [a], Boualem Bendib [a]

[a] Group of Research: Photovoltaic System, Unit of Development of Solar Equipments (UDSE), EPST/CDER—Route Nationale No: 11, Bou-Ismaïl LP 365, Tipaza 42415, Algeria
[b] Laboratory of Communication Devices and Photovoltaic Conversion (LCDPVC), Polytechnic National School, 10 Avenue Hacen Badi, El Harrach, Alger, Algeria
[c] Electrical Engineering Laboratory—University Joseph Fourier-G2Elab, Grenoble, France

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ABSTRACT

In this paper a detailed sizing method of stand-alone Photovoltaic–Wind hybrid systems is proposed and evaluated by the design and the development of flexible software basing on techno-economic analysis and using Object-Oriented Programming. First, a short review of the different sizing programs is given after, a detailed sizing methodology for PV–Wind systems is presented; finally, new software for sizing such systems is conceived. This computer program is building around fundamentals photovoltaic and wind generators models, storage capacity model, Loss of Power Supply Probability (LPSP) algorithm and a proposed techno-economic algorithm to determine the system that would guarantee a reliable energy supply with a lowest investment.

Contents

* Corresponding author. Tel.: +213 774 540 065.
E-mail addresses: belmilih@yahoo.fr (H. Belmili), mourad_haddadi@yahoo.fr (M. Haddadi), Seddik.Bacha@g2elab.inpg.fr (S. Bacha).

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1. Introduction

Naturally renewable sources are not constant so their association with conventional ones permits their uninterrupted power generation. Hybrid Energy Systems (HES), combine two or more complementary renewable sources like wind and solar and one or more conventional sources like diesel generator [1]. Generally, most of hybrid systems have a system of energy storage [2]. There are many energy storage systems, like, electrochemical, inertial and hydrogen [3]. The configuration of hybrid system resulting from a design based on the resource available and the constraints of uses, in principle the use in maximum of the renewable energy resources and the optimization of the power supplied quality.

Hybrid PV–Wind systems (Fig. 1) offer the most adequate solutions for the electrification of remote areas; the combination and the ratio of the two types of energy depending greatly on the resources locally available in each geographical area. These resources can be evaluated only after a period typically one year of monitoring of the basic parameters (wind speed, solar radiation and temperature), which are necessary for sizing and implementing such systems in the respective areas.

2. Sizing methods and simulation programs review

The aim for an optimum sizing of stand-alone photovoltaic–wind hybrid systems is to guarantee the lowest investment with a reasonable and full use of the renewable energies sources, with energy storage optimization in terms of load satisfaction. Various optimization techniques of sizing have been reported in the literature such as proposed by Markvart [4], which studied a PV/Wind hybrid system and determine the sizes of the PV array and wind turbine, by using the measured values of solar and wind energy at a given location. Another technique for the sizing stand-alone hybrid photovoltaic–wind systems has been developed by Bagul et al. [5]. This technique has important advantages over the original three event techniques: A probabilistic approach is used to get to the results. A general method has been developed to determine the sizing and the operation control of hybrid systems. The operation control and sizing selection method is based on genetic optimization techniques [6]. Kellogg et al. in [7] have developed a numerical algorithm for generation unit sizing hybrid PV/wind power generating as stand-alone systems. Marwali et al. in [8] proposed a methodology for cost calculating production of hybrid systems. Also a probabilistic performance assessment method was developed by Karaki et al. [9]. A methodology is developed to determinate the optimal size of PV-hybrid subsystems and to optimize the stand-alone system management [10]. Diverse methods including probabilistic and/or deterministic approaches have been developed to assess the performance of these hybrids systems. Energy flow and battery storage system was modeled to obtain optimal size of a PV and wind generators. A techno-economic analysis for stand-alone PV/wind hybrid energy system is presented by Celik [11]. This method is complete by Ai et al., which gives more accurate and practical. Also, neural network and genetic algorithm may be used and combined for sizing and controlling hybrid energy system to giving optimum solution [12,13].

To evaluate the performance of the hybrid solar/wind systems, several software tools are available for designing hybrid systems, such as HYBRID2, HYBRIDS, HOMER and HOGA [14].

HYBRID2 is software for simulation hybrid system. It was developed by the Renewable Energy Research Laboratory (RERL) (University of Massachusetts). HYBRID2 simulations are very precise (time intervals from 10 min to 1 h) [15].

HOMER (Hybrid Optimization Model for Electric Renewable) developed by National Renewable Energy Laboratory. It is a time-step simulator using hourly load and environmental data inputs for renewable energy system assessment; it facilitates the optimization of renewable energy systems based on Net Present Cost for a given set of constraints and sensitivity variables. HOMER consists of a library including photovoltaic generators, batteries, wind turbines, hydraulic turbines, AC generators, fuel cells, electrolyzers, hydrogen tanks, AC–DC bidirectional converters, and boilers. The loads can be AC, DC, and/or hydrogen loads, as well as thermal

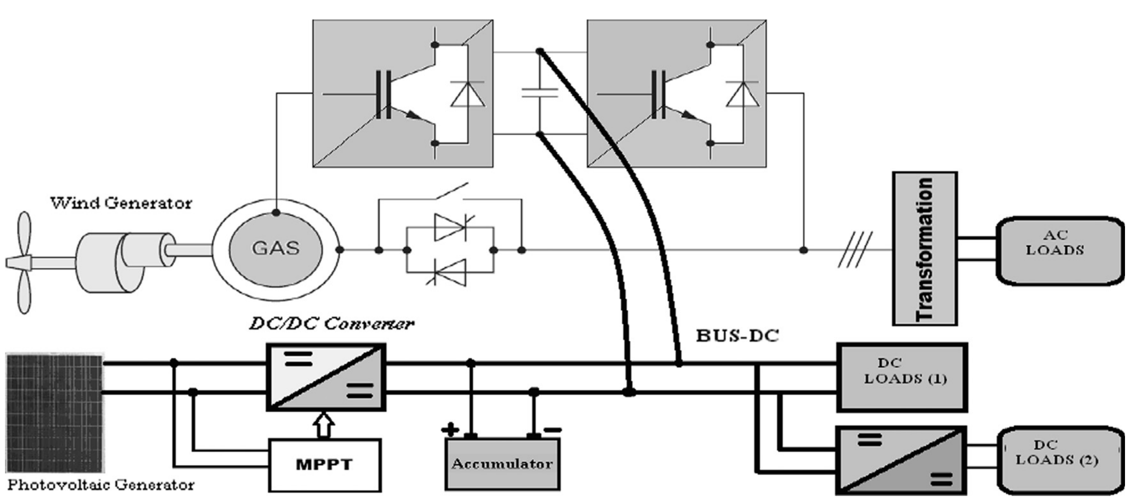

Fig. 1. Configuration of the studied stand-alone PV–Wind hybrid system.

loads. The user must select the components of the model to represent the architecture of his network. For optimization purposes, technical and financial data for each selected component must be entered. It simulates the operation of a system by making energy balance calculations for each of the 8760 h in a year. For each hour, it compares the electric demand in the hour to the energy that the system can supply in that hour, and calculates the flows of energy to and from each component of the system. The tool also decides for each hour how to operate the generators and whether to charge or discharge the batteries (dispatch strategies: cycle charging and load following). When sensitivity variables are selected as inputs, HOMER repeats the optimization process for each sensitivity variable specified. At the end of the simulation, the different system configurations are classified by their total NPCs [16,17].

HYBRIDS, is a Microsoft Excel spreadsheet-based renewable energy system assessment application and design tool, requiring daily-average load and environmental data estimated for each month of the year. It developed at the University of Massachusetts and the National Renewable Energy Laboratory. This software uses a combined time series/probabilistic method. The time series approach is useful for long term predictions but, for an accurate diesel dispatch, Hybrid 2 accounts for short term fluctuations in the wind and load power. This time steps can vary from 10 min to several hours, and here appears the probabilistic or statistical approach, applied in each interval. Both the approaches mentioned, assure that energy is conserved throughout the entire simulation, and that the Hybrid 2 model is internally consistent. The probabilistic approach can be explained due to the fact that the method is based on its use of probability density functions for addressing the statistics of generation and load short term fluctuations. Using the time series/probabilistic method implies that the algorithm assumes mean values of the various inputs and internally calculated values. Hybrid2 assumes that this values are randomly distributed about the mean value used and, furthermore, that the distribution values can be described by a probability density function. The probability density functions (p.d.f) used are the normal Gaussian and in some cases, the Weibull distribution. These p.d.f are used in each time step to find expected maximum and minimum values, the fraction of time in which those values may be within a certain range, and the amount of energy that may be required or available in this range [14]. Hybrid2 assumes that the wind speed, wind power, and load are all normally distributed over the time step. This assumption is based on previous work that showed that the wind speed and wind power are approximately normally distributed around the mean value over time intervals of approximately 10 min [14]. In addition, other work indicates that the electrical load for an autonomous diesel grid is also approximately normally distributed over a short time interval [14,15]. Different to HOMER, HYBRIDS can only simulate one configuration at a time, and is not designed to provide an optimized configuration [16–18].

HOGA (Hybrid Optimization by Genetic Algorithms) is a hybrid system optimization program developed by the Electric Engineering Department of the University of Zaragoza-Spain. The control and the optimization are carried out by means of Genetic Algorithms, and can be mono-objective or multi-objective. It contains a data base of different compounds like photovoltaic panels, wind turbines, hydroelectric turbines, fuel cells, as well as batteries, regulators, inverters, rectifiers, also a different system loads. HOGA Optimization is achieved by minimizing total system costs throughout the whole of its useful lifespan, when those costs are referred to or updated for the initial investment NPC (Net Present Cost). Optimization is therefore financial (mono-objective). However, the program allows multi-objective optimization, where additional variables may also be minimized: CO_2 emissions or unmet load (energy not served), as selected by the user. Since the cost, emissions, or unmet load are mutually counterproductive in many cases, more than one solution is offered by the program, when multi-objective optimization is required [19,20].

The developed software employs a techno-economic approach to determine the system that would guarantee a reliable energy supply with a lowest investment. This software is mainly characterized by a simple user interface. Were the user followed five clear steps and they can easily enter the specification parameters of their system. As it can easily introduce the cost of components NPC (Net Present Cost) also costs of maintenance and replacement (M&R) taking into account the money exchange rate variation in the international market. The following table represents a resume comparison between different tools under discussions (Table 1).

3. PV–Wind sizing system: Applied methodology

3.1. Fundamental equations

For sizing hybrid energy systems some basic equations was established [21–23].

The first equation describes the photovoltaic power generation.

$$P_{PV} = \eta_{pvg} \times A_{pvg} \times G_{ir} \tag{1}$$

with $A_{pvg}(\mathrm{m}^2)$ is the surface of PV generator, η_{pvg} the efficiency of conversion, given by

$$\eta_{pvg} = \eta_r \times [1 - \beta \times (T_c - T_{cref})] \tag{2}$$

- η_r Photovoltaic module reference efficiency.
- β Temperature coefficient witch supposed constant for silicon solar cells.
- T_{cref} Reference solar cell temperature (°C).
- G_{ir} Global solar irradiation (W/m^2).
- T_c Solar cell temperature it gives by

$$T_c = T_a + \left(\frac{NOCT - 20}{800}\right) \times G_{ir} \tag{3}$$

These different parameters are gives by the manufacture of each kind of photovoltaic module.

The second equation describe the wind power generation. To determine this power it is necessary to know the wind speed [24–26]. So to calculate the wind speed in a specific level a vertical extrapolation is establish

$$\frac{v(z)}{v(z_a)} = (\frac{z}{z_a})^{\alpha} \tag{4}$$

where:$v(z)$,$v(z_a)$ and α: represent the wind speed in anemometer level, the wind speed in the desired level and the coefficient characterized wind cutting.

The Weibull distribution of wind is given by [27]

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp - \left(\left(\frac{v}{c}\right)^k\right) \tag{5}$$

Each wind generator is characterized by a power diagram, which depending on functioning speeds. The following equation gives a model to calculate the output power of this generator [28,29].

$$P_w(v) = \begin{cases} P_n \times \frac{v - v_{dem}}{v_n - v_{dem}}, v_{dem} \le v \le v_n \\ P_n, v_n \le v \le v_{max} \\ 0, \text{else} \end{cases} \tag{6}$$

with

- P_n=nominal power,

Table 1
Comparison of commercial programs for sizing hybrid systems.

Specifications	HOMER
Based method	*A program based time-step simulation with probabilistic approach and an economic analysis*
Resources	*Solar, wind, hydro, biomass, fuel*
Load and environmental data	– *Primary, deferrable and thermal load* – *Hourly load and environmental data inputs*
Compounds	– *PV modules, wind turbine, hydro, generator, grid, battery, converter, Electrolyzers*
Economic	*Annual real interest rate, project lifetime, cost of unmet load, system fixed capital cost, system fixed operation and maintenance (O&M) cost, carbon tax*
Simulation and analysis	– *Estimates the cost and determines the feasibility of a system design over the 8760 h in a year* – *Simulates each system configuration and displays list of systems sorted by net present cost (NPC)* – *Performs an optimization for each sensitivity variable*
Optimization	*Contains the values of each optimization variable that are used to build the set of all possible system configurations*
Results	– *Simulate various configuration* – *Minimizing total cost referred to the Net Present Cost*
HYBRIDS	
Based method	*Microsoft Excel spreadsheet-based using combined time series and probabilistic method*
Resources	*Solar, wind, fuel*
Load and environmental data	– *Daily-average load* – *Environmental data estimated for each month of the year*
Compounds	*PV panels, wind turbine, diesel generators, batteries*
Economic	*Calculated the NPC*
Simulation and analysis	*Used 1-h intervals in the simulation*
Optimization	*No optimization provided*
Results	*Can only simulate one configuration at a time*
HYBRID2	
Based method	*A combined probabilistic/time series computer model*
Resources	*Site parameters as well as time series data of wind, solar irradiation and ambient temperature*
Load and environmental data	– *Primary, deferrable, optional and heating load* – *Daily average load and estimated environmental data*
Compounds	*Wind turbine, PV module, diesel, dump load, battery, converter, synchronous condenser and dispatch strategy*
Economic	*Costs of the various components as well as economic parameters that are used to evaluate the economic performance of the system*
Simulation and analysis	*Include values of a number of system variables for each time step. system variables include the power going to each type of load, the unmet load, the power produced by each generating unit, the power going into storage, the power conversion losses, the hybrid system diesel fuel consumption, the base case system diesel fuel consumption, and the time step energy balance*
Optimization	*Give the cumulative energy flows and fuel consumption during the simulation run*
Results	*Simulate only one configuration but the simulations are very precise (time intervals from 10 min to 1 h)*
HOGA	
Based method	*A program based genetic-algorithm to sizing and control variables of the system add to the probabilities analysis*
Resources	*Diesel generation, photovoltaic, wind, batteries, Mini-hydro, Fuel cell, electrolyzers,*
Load and environmental data	– *Daily average load* – *Daily average environmental data*
Compounds	*PV panels, wind turbines, hydroelectric turbines, fuel cells, H2 tanks, and electrolyzers, batteries, battery charge regulators, inverters, rectifiers and AC generators* *Different system loads are possible: electric AC, electric DC, hydrogen, and water pumping load, Thermal load*
Economic	*Minimizing total cost referred to the Net Present Cost in mono-adjective approach and minimizing total cost referred to NPC and costs of* CO_2 *and/or unmet load in multi-objective approach*
Simulation and analysis	– *Uses very accurate models for resources, for compounds and for economical calculations* – *Includes an advanced aging batteries model, taking into account corrosion, weighted cycles (effects of SOC, current, acid stratification …) and temperature* – *Includes an advanced model of optimization control strategies*
Optimization	– *Optimizes the slope of the PV panels,* – *Allows the selection of the currency to be used in the economical calculations* – *Calculates life cycle emissions* – *Allows the buying and selling energy to the electrical grid*
Results	*More than one configuration is offered, when multi-objective optimization is sought*

– v_{dem}=starting speed,
– v_n=nominal speed,
– $v_{\max}$=maximum speed,

The third part of this system is the storage part. The mathematical model of state of battery charging (SOC_{bat}) is depending on precedent state of charge, and on produced energy by

booth wind generator E_W and PV generator E_{PV}, also with load demand E_L [15,16]. To calculate $\mathrm{SOC_{bat}}$ of batteries there is two scenarios

3.1.1. First scenario

If $E_W(t) \geq E_L(t)$, batteries are in charging process, and the instantaneous storage capacity $\mathrm{SOC_{bat}}(t)$ is given by:

$$\mathrm{SOC_{bat}}(t) = \mathrm{SOC_{bat}}(t-1) + (E_{\mathrm{PV}}(t) + (E_W(t) - E_L(t)) \times \eta_{\mathrm{inv}}) \times \eta_{\mathrm{bat}} \quad (7)$$

with:

$$\begin{cases} E_{PV}(t) = P_{PV}(t) \times \Delta t \\ E_W(t) = P_W(t) \times \Delta t \\ E_L(t) = P_L(t) \times \Delta t \end{cases} \quad (8)$$

P_{PV} (t), P_W (t), P_L (t): Are, respectively, PV generator power in an instant « t », Wind generator power in the same instant « t », and load demand in this instant « t » [30,31].

- Δt Step time of simulation
- η_{inv} Inverter efficiency
- η_{bat} Batteries ***charging efficiency, generally it depends on charging current. It is between* [0.65 *and* 0.8]**.

3.1.2. Second scenario

If $E_W(t) \prec E_L(t)$ we have two possibilities:

1- If $E_{\mathrm{PV}}(t) \geq (E_L(t) - E_W(t))/\eta_{\mathrm{inv}}$, batteries are in charging state and the storage capacity is given by

$$\mathrm{SOC_{bat}}(t) = \mathrm{SOC_{bat}}(t-1) + \left(E_{\mathrm{PV}}(t) - \left(\frac{E_L(t) - E_W(t)}{\eta_{\mathrm{inv}}}\right)\right) \times \eta_{\mathrm{bat}} \quad (9)$$

2- If $E_{\mathrm{PV}}(t) \prec (E_L(t) - E_W(t))/\eta_{\mathrm{inv}}$, corresponding to discharging batteries, which characterized by the following relationship

$$\mathrm{SOC_{bat}}(t) = \mathrm{SOC_{bat}}(t-1) + \left(E_{\mathrm{PV}}(t) - \frac{E_L(t) - E_W(t)}{\eta_{\mathrm{inv}}}\right) \times \frac{1}{\eta_{\mathrm{disch}}} \quad (10)$$

With η_{disch}, batteries discharging efficiency, it supposed equal to 1.

In all scenarios the state of batteries charging must satisfy the following condition

$$\mathrm{SOC_{bat\_\ min}} \leq \mathrm{SOC_{bat}}(t) \leq \mathrm{SOC_{bat\_\ max}} \quad (11)$$

where

$\mathrm{SOC_{bat\_\ min}}$ and $\mathrm{SOC_{bat\_\ max}}$ are the limits states of batteries charging.
$\mathrm{SOC_{bat\_\ max}}$ is considered like the nominal capacity of the storage system,

The inferior limit is given by

$$\mathrm{SOC_{bat\_\ min}} = \mathrm{DOD} \times C_{\mathrm{bat}\_n} \quad (12)$$

DOD (%) represents the discharging batteries depth.

The total batteries capacity [W h], depending principle on the number of autonomy days 'N_{da}', on the produced energy by all renewable sources without storage and the daily consumption [31,32].

We calculate for each day "d" of the year the different between the energy demands and produced once. This strategy we can permit to identify the variation of $\mathrm{SOC_{bat}}$.

$$E_d(t) = E_L(t) - E_p(t) \quad (13)$$

So

$$E_p(t) = E_W(t) + E_{\mathrm{PV}}(t) \quad (14)$$

$$E_d(t) = \textstyle\sum_{t=1}^{24} E_d(t) \;\text{ if }\; E_d(t) mac; sc; 0 \quad (15)$$

In the case of energy deficiency, we research the maximal daily difference between the energy demands and produced once along of a year. To determine the nominal capacity we use the following relation [32,33]

$$C_{\mathrm{bat}\_n} = \frac{N_{da} \times \text{ Max } \times E_d(t)}{\eta_{\mathrm{disch}}} \quad (16)$$

The state of batteries charging limits are defines with

$$\mathrm{SOC_{max}} = C_{\mathrm{bat}\_n} \quad (17)$$

$$\mathrm{SOC_{min}} = \mathrm{DOD} \times C_{\mathrm{bat}\_n} \quad (18)$$

The principle objective of sizing this systems is to determine their optimal configuration (size of photovoltaic generator, size of wind generator and the capacity of the storage system) to satisfy the load demand. Several methods for sizing hybrid energy system, was discussed in the introduction. In this development the LPSP (Loss of Power Supply Probability) is used associated with a technical–economic approach and mathematical models. This method can offered a simulation of all configurations possible of the system can satisfy the load profile demand. The economic approach is applied to give the optimal one.

3.2. Methodology description

During the system functioning different cases were distinguished

a- The load power demand is lower than the produced power by the wind generator ($P_L \prec P_W$). In this case the energy surplus and the energy produced by the photovoltaic generator will be storage on the accumulator park, and the nouvelle state of battery charging is calculated like the equation number (07). If this state of charge will be higher than the $\mathrm{SOC_{bat\_max}}$, the surplus will be conducting to the auxiliary loads.
b- The load demand is superior to the wind generator produced energy($P_L mac; sc; P_W$). In this situation the energy deficiency ($P_L - P_W$) is compensating by photovoltaic generator produced energy, and the state of charge is calculated by the Eq. (8). If the photovoltaic produced energy cannot satisfy the load, i.e. $P_{\mathrm{PV}}(t) \prec (P_L(t) - P_W(t))/\eta_{\mathrm{inv}}$ the batteries will discharge to compensate the energy deficiency with the respect of the discharging limit ($\mathrm{SOC_{bat}} mac; sc; \mathrm{SOC_{bat\_\ min}}$) and the state of batteries charging can be calculated by using the Eq. (9).

In this case (b), if the batteries cannot satisfy the load demand in a desired period « t », this deficiency is named LPS (loss of power supply). It can be calculated with the following relation

$$\mathrm{LPS}(t) = (P_L(t) - P_W(t)) \times \Delta t - (P_{\mathrm{PV}}(t) \times \Delta t + C_{\mathrm{bat}}(t-1) - \mathrm{SOC_{bat\_\ min}}) \times \eta_{\mathrm{inv}} \quad (19)$$

3.3. Loss of power supply probability (LPSP) description

This sizing method consists in determining the optimal number of the batteries and the photovoltaic modules according to the optimization principle knowing: the reliability, which is based on the concept of the probability of loss of energy (Loss of Power Supply Probability 'LPSP') [35,36], and

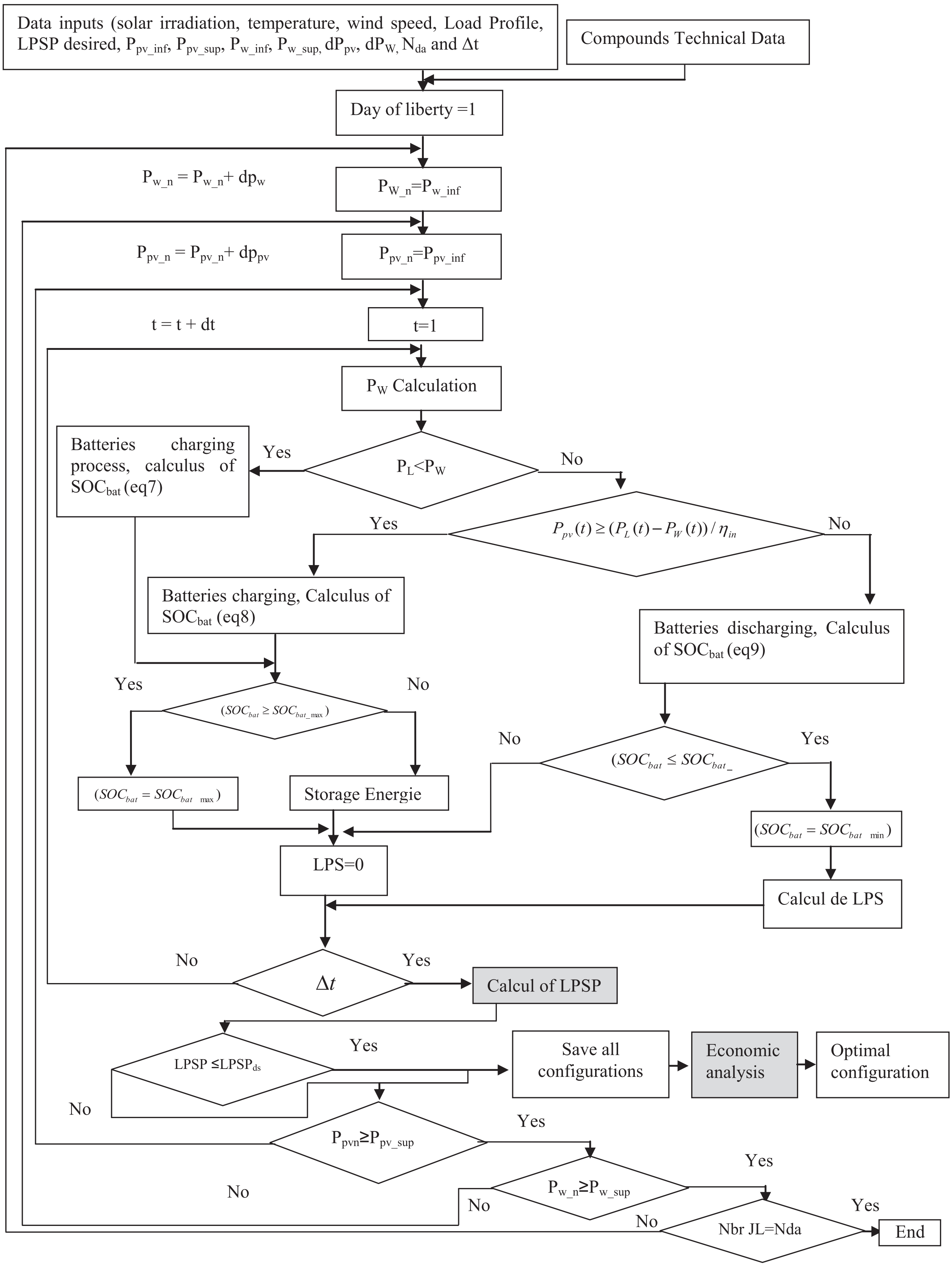

Fig. 2. Flowchart of the developed algorithm.

on the cost of the system. 'LPSP' is defined as being the fraction of the deficiency energy and that required by the load. It explains the rate of load dissatisfaction, in term of batteries charging statement. Otherwise it is defining such as the fraction of all energy losses and the energy demand in a define period of functioning (for our study we use t=one year) like it

represent on theses expression [22,23]

$$LPSP = P_r\{E_{bat}(t) \le E_{bat\_min} \text{ for } t \le t\} = \frac{\sum_{t=1}^{T} LPS(t)}{\sum_{t=1}^{T} P_L(t) \times \Delta t} \quad (20)$$

i.e. the probability that the load statement, at any moment "t", is lower or equal to the minimal edge of the supplied energy in battery E_{bat_min}. $E_{bat}(t)$ is the energy stored in the battery at any moment t, expressed in [W h] [23,24]. This method presents the advantage that the introducing of the wind generator permits to minimize the cost of the photovoltaic stand-alone system, by the minimizing the size of the photovoltaic generator and the storage capacities (number of batteries) [33,36,37].

3.4. The technical–economic developed algorithm analysis

Based on the LPSP description method, an algorithm was developed;

- P_{PV_inf}, P_{PV_sup} and P_{W_inf}, P_{W_sup} are parameters which represent the limits of photovoltaic generator power production and wind generator power production, respectively.
- dP_{PV} and dP_W represents the variation steps of photovoltaic and wind generator powers.
- dt represent the simulation step.

The inputs data of this algorithm are:

- The average values of solar irradiation, temperature and wind speed of each typical day of month in the year.
- The desired value of the LPSP on one year.
- Parameters of the different system compounds.

This algorithm permits the identification of the (P_{PV}, P_W, N_{bat}) triple matrix of all possibilities which can satisfy the LPSP. The relationship between these variables is not linear. Only the economic analysis can permit to select the optimal sizing of the studied system.

3.5. The economic analysis and the identification of the optimal configuration

Principally there are three main cost categories:

3.5.1. The initial cost

It is related to the purchase cost added to installation cost

$$C_i = P_W \times C_{i\_W} + P_{PV} \times C_{i\_PV} + N_{bat} \times C_{i\_bat} + S_{inv} \times C_{i\_inv} \quad (21)$$

with:

- C_{i_W}: The initial cost of the wind system
- C_{i_PV}: The initial cost of the photovoltaic system
- C_{i_bat}: The initial cost of the storage system
- C_{i_inv}: The initial cost of the inverter
- S_{inv}: The apparent power of the inverters.

3.5.2. The maintenance cost

In the developed software a percentage of the initial cost for each compound is gives for a period of a year

$$C_m = (P_W \times C_{i\_W} \times m_W + P_{PV} \times C_{i\_PV} \times m_{PV} + N_{bat} \times C_{i\_bat} \times m_{bat} + S_{inv} \times C_{i\_inv} \times m_{inv}) \times lf_{sys} \quad (22)$$

- m_W: Percentage of the annual maintenance of the wind system
- m_{PV}: Percentage of the annual maintenance of the photovoltaic system
- m_{bat}: Percentage of the annual maintenance of the storage system
- m_{inv}: Percentage of the annual maintenance of the inverters
- if_{sys}: Life time of the system [years].

3.5.3. Compounds replacing cost

Each compound of the system have lifetime, it must after this lifetime be replaced by another.

$$C_m = P_W \times C_{i\_W} \times \frac{(lf_{sys} - lf_W)}{lf_W} + P_{PV} \times C_{i\_PV} \times \frac{(lf_{sys} - lf_{PV})}{lf_{PV}} + N_{bat} \times C_{i\_bat} \times \frac{(lf_{sys} - lf_{bat})}{lf_{bat}} + S_{inv} \times C_{i\_inv} \times \frac{(lf_{sys} - lf_{inv})}{lf_{inv}} \quad (23)$$

$lf_{sys}, lf_W, lf_{PV}, lf_{bat}, lf_{inv}$: The lifetimes of all the system, the wind generator, the photovoltaic generator, storage system and the inverter, respectively. Generally the wind generator and the photovoltaic generator have lifetime's approaches to the global system, so their replaced costs are neglected and can be equal to zero [33,34,38]. The global cost of all functioning period is given by

$$C_G = C_i + C_m + C_r \quad (24)$$

In this case, it is very important to introduce the inflation ratio, which can take in consideration to the dynamic of money changing values. The following figure represents the flowchart of the proposed algorithm (Fig. 2).

4. Sizing developed program: Implementation

The following section presents the implementation of the designed program under windows. These windows described the discussed methodology above. This software appears with a principal window (Fig. 3) resume all steps for sizing off-grid

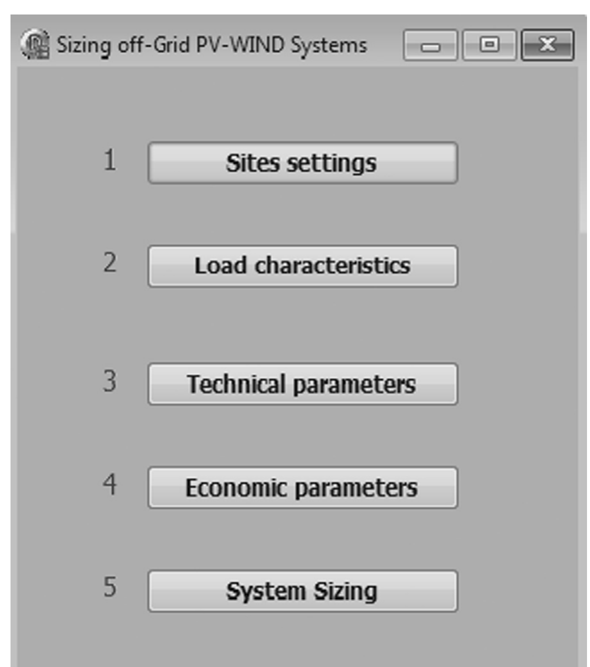

Fig. 3. The five step to sizing PV–Wind hybrid system.

PV–Wind systems. These steps are:

- *Sites settings*: introduce the measured environmental data of the site of implementation,
- *Load characteristics*: establish the load profile,
- *Technical parameters*: describe the compounds constitute the system,
- *Economic parameters*: define the parameters of the economic analysis,
- *System sizing*: start simulating and optimization of the system and give results.

At each selection of these five buttons, a new window appears; allowing the user to define the various parameters characterized his system. In the nest section these windows are presented one by one in order.

4.1. Sites settings

In this window (Fig. 4), the user can select a location from a saved database to implement his system. This database provides all necessary values for simulation, such air temperature, horizontal solar irradiation, atmospheric pressure and wind speed.

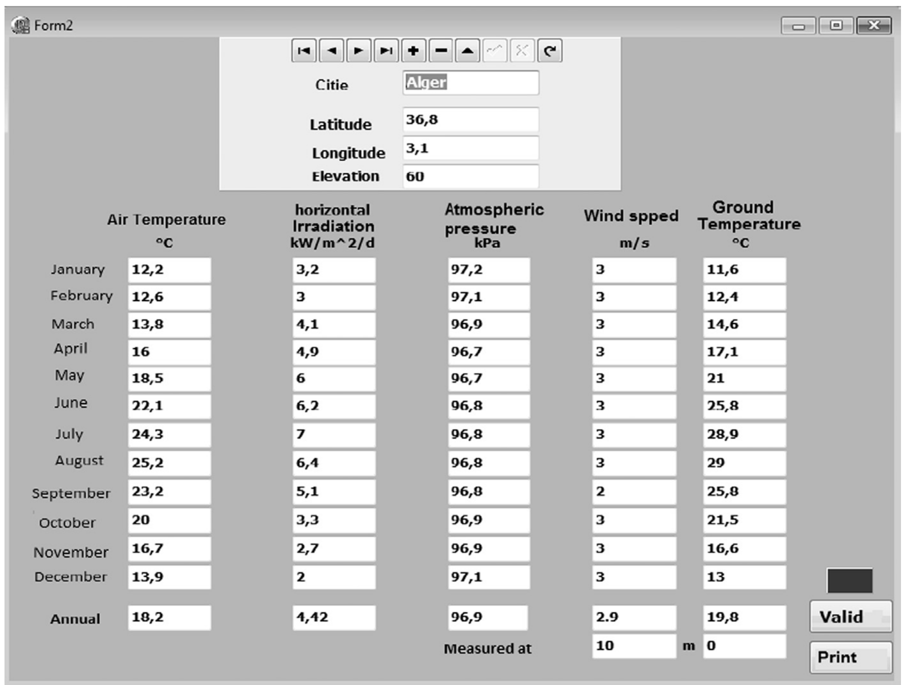

Fig. 4. Sites caracterizations.

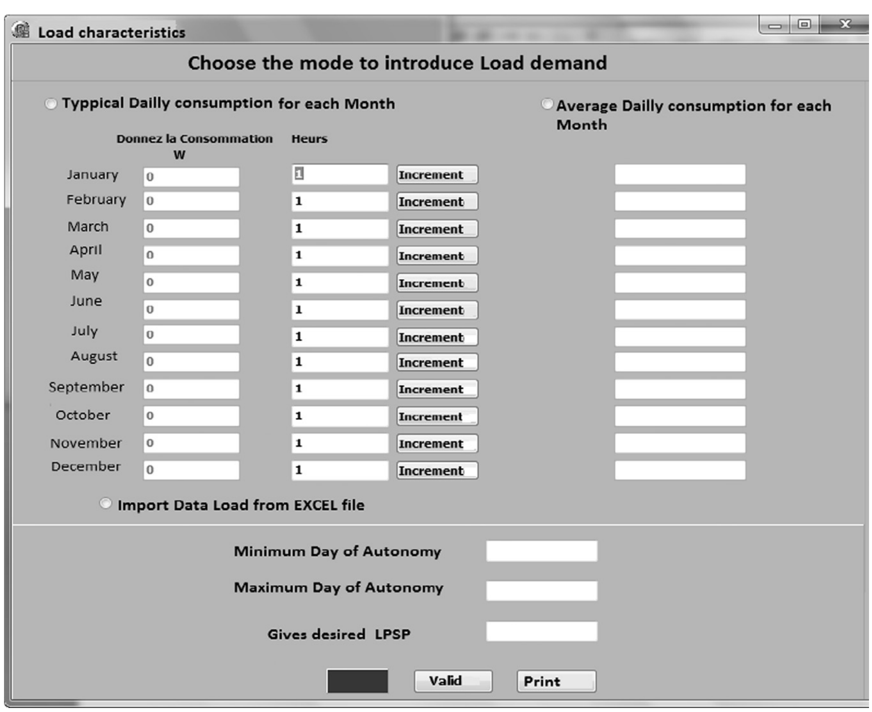

Fig. 5. Load profile introducing.

4.2. Load characteristics

This step is crucial; the user specify their power consumption profile. Three choices are available:

– *Daily average load:* where it should populate the value of his office during the 24 h of a typical day for each month of the year for 12 months.
– *Monthly average load:* where it should populate the value of his office during a day of each month of the year.
– *Imported data load from an EXCEL file*: the user can import data profile of a real consumption saved under an EXCEL file.

The following figure illustrates this (Fig. 5):

For the daily average load, whenever the user entered a value, they must increment time by clicking the "increment" button (Fig. 6).

Under the same window (Fig. 5) the user introduce: the minimum and the maximum days of autonomy and the desired LPSP. The validation is done by clicking on the "valid" button, where the icon red set in green for confirming validation.

4.3. Technical parameters

A click on the technical parameters button, a new window appears. This window specifically brings all the technical parameters characterizing the system to be sizing. It is unscrewed in three fields:

– *Adjustment range production system*: the user should specify the maximum and the minimum power and the increment step of power for each generator (PV and wind), Fig. 7.
– *Parameters of photovoltaic generator*: to calculate the power generation of PV generator, the user ought to introduce the performance of the used panels (commercial modules) especially: module efficiency, the nominal operating cell temperature (NOCT), reference or ambient temperature, the temperature coefficient β [33], Fig. 8.
– *Parameters of wind generator*: under this figure the user should specify the ranges of variation of used wind turbines. There are three fields to complete, and in each one they inter the power range of wind turbine with the speeds characteristics: starting speed, Nominal and Maximal speeds (that according to datasheet of the manufacturers) (Fig. 9).

4.4. Storage settings

To define the total capacity storage of the system, the user must enter the storage capacity in [A h] of a single battery. Also, all parameters described the performance of charging and discharging, the depth of discharge and voltage rating must be correctly introducing to guaranty a good result of simulation, Fig. 10.

At the end of a check do not forget to also fill in is the box that defines the performance of the inverter use, typically it is around 90–98% [30], and once the user finish entering all parameters specified must be validated by a click on the red icon and the green confirms validation.

4.5. Economic parameters introduction

In the step number four (see Fig. 3) to sizing these systems, is the introducing of the economic parameters which are very important to determine optimal configuration of the system according to the cost of investment and to the cost of power generation. When the user selects this window, they can introduce the initial costs of all the compounds constitute the system in $/W

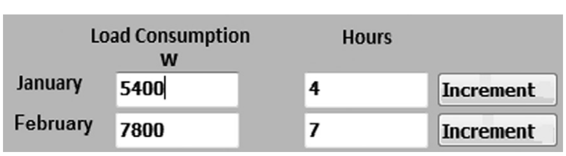

Fig. 6. Average monthly consumption.

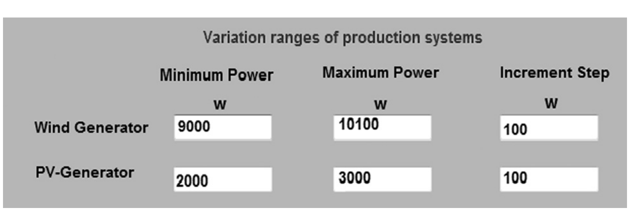

Fig. 7. Variation interval of production sources.

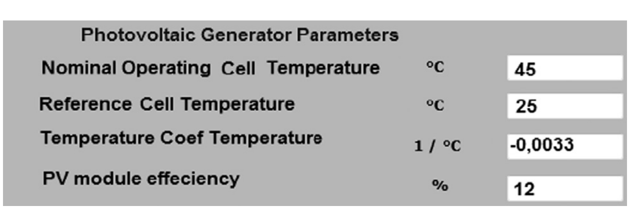

Fig. 8. PV Generator parameters.

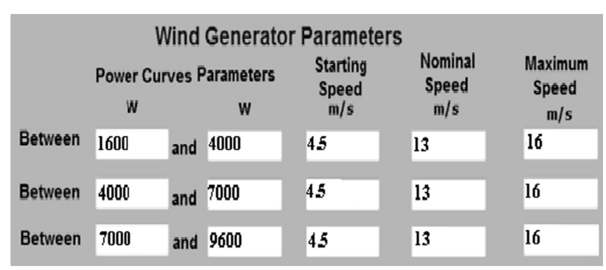

Fig. 9. Wind generator parameters.

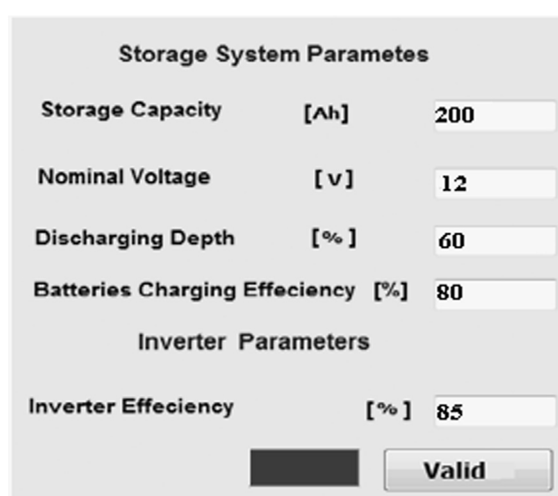

Fig. 10. Storage system and inverter parameters.

also the annual maintenance costs and lifetimes of each equipment of the system, Fig. 11.

4.6. System sizing: Simulation and optimization

Arrival in this final and crucial step of “simulation and optimization”, the user finishes introducing all parameters characterizing their system, a reminder before the design is that the user is strongly advised to check the validation of the values recorded after each step, verifying that the red icon before the “OK” button is set to green in each time. Selecting this button correctly can lead the user to the final step (step number five—Fig. 3) to sizing correctly the described hybrid system. The following figure represents the window that used to starting simulating of the system.

This program can simulate the operation of a system by making energy balance calculations for each hour in a year. For each hour, the program compares the produced power in the hour to the electric load demand in that hour. In the same time it decides how to charging and discharging batteries and whether to operate the PV and wind generators.

The optimization approaches based on LPSP and the economic analysis. It becomes after simulating of all configurations possible of the system. In the end the program displays of a list of feasible configurations, sorted by the optimal one referred to the minimum cost. The list can be scanned for other feasible systems. The optimum one is put it at the top of the list.

When the user clicks “start sizing” in the window (Fig. 12), the program start the simulation and the optimization, and displays the following results described the optimal system configuration:

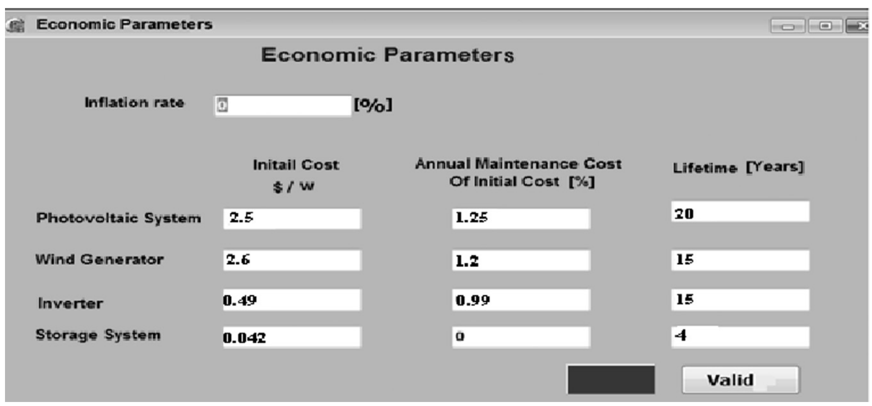

Fig. 11. Economic parameters.

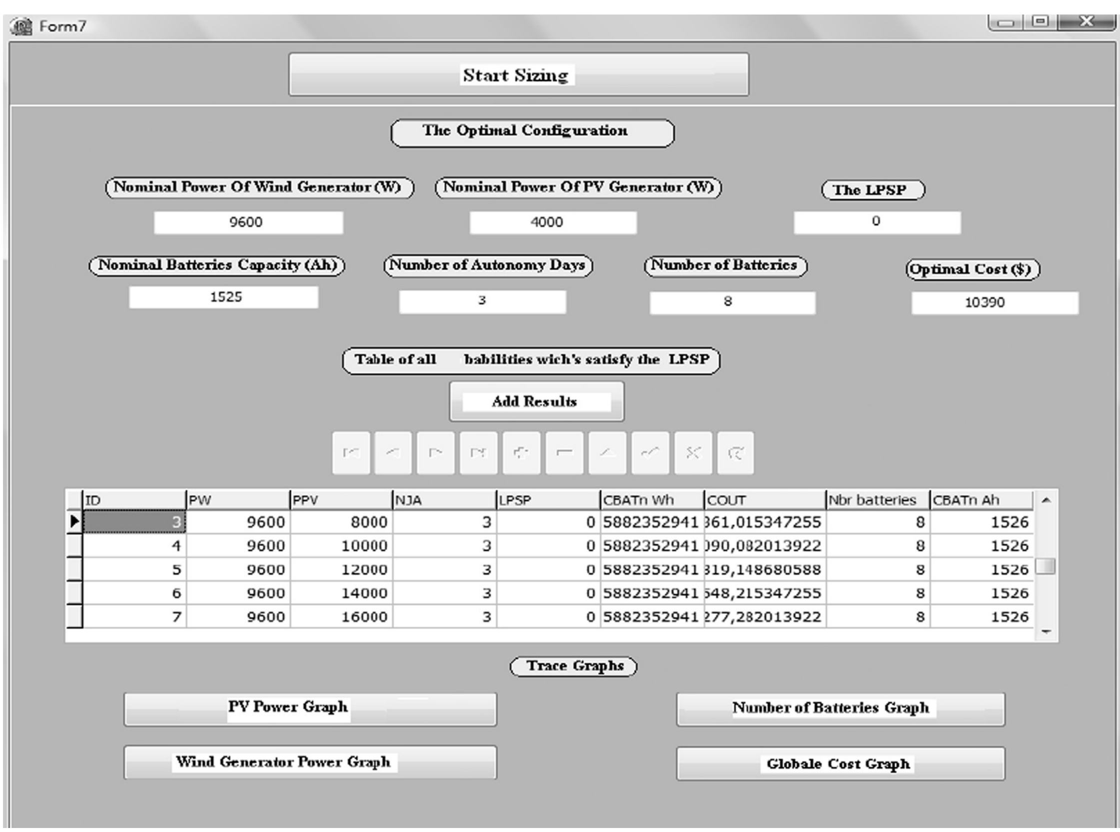

Fig. 12. Screen of simulation results.

Table 2
Developed program specifications.

Specifications	*Developed program*
Based method	A program based on time-step simulation and mathematical models with probabilistic approach and economic analysis
Resources	Solar, wind
Load and environmental data	– Daily average load or Monthly average load or imported data load from an EXCEL file – The average values of environmental data for each typical day of month in the year
Compounds	– PV modules, wind turbine, batteries – Designs off-grid power systems
Economic	– Simulates each system configuration and displays list of systems sorted by net present cost (NPC), compounds lifetime maintenance and replacement (M&R) costs
Results	Simulate various configuration
Optimization	Includes an advanced techno-economic strategy to build a set of all system configurations and to minimize total cost referred to the Net Present Cost, maintenance and replacement costs with introducing the money exchange variation and inflation rate
Results	– Simulate various configuration

– The optimal power of the wind generator to be used;
– The optimal power of photovoltaic generator;
– The optimal batteries capacity;
– The number of batteries to storage energy;
– The number of autonomy days;
– Total net present cost for the whole system.
– Desired LPSP.

Other configurations that satisfy the condition specified in the value of the LPSP are classified in a table, to fill the calculated results from the user presses the button "Add Results", in this way the program displays the total list of possible configurations preceded by the optimal one. Graphs are provided by clicking different buttons:

– "Draw the graph of PV power generation"
– "Draw the graph of wind power generation"
– "Draw the graph of the number of batteries"
– "Draw the graph of the overall cost".

The next table gives a resume of the developed program specifications, which can be compared with the commercial ones (Table 2).

5. Conclusion

In this work the LPSP algorithm with a new proposed techno-economic algorithm for sizing standalone PV–Wind system was implemented. This strategy depend principle on costs study taking into account the different compounds costs using in the system, their lifetimes also the load profile and the meteorological characteristics of each installation site. This method was implemented under a computer program, which become practical, interactive and easy to use. This elaborated program permits to determine the optimum size of the battery bank and the PV array for a given load and a desired loss of power supply probability taking into account the minimum energy cost which is depends generally on investment cost, operation and maintenance costs and the depreciation period. The competitiveness of the developed program in their first version is the simple user interface under windows.

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